BENEFITS OF APPLYING SECONDARY VOLTAGE CONTROL SCHEMES TO THE BRAZILIAN SYSTEM

G. N. Taranto N. Martins D. M. Falcão A. C. B. Martins M. G. dos Santos
COPPE/UFRJ CEPEL COPPE/UFRJ FURNAS ONS
Rio de Janeiro, RJ – Brazil

Abstract - This paper presents preliminary results of the investigations related to the prospective application of a hierarchical coordinated voltage control to parts of the Brazilian EHV network. The paper focuses on the Secondary Voltage Control (SVC) hierarchical level, with emphasis on voltage control by power plants and synchronous condensers. The study system analyzed is the Rio de Janeiro (Rio) Area, which is an energy importing area. Results refer to a heavy load condition, typical of a hot summer day.

Keywords: Coordinated Voltage Control, Secondary Voltage Control, Voltage Security, Hierarchical Control.

1. Introduction

Electric utilities in some European countries [1-3] have adopted strategies that maintain an adequate voltage profile at key regions of the system on different loading scenarios. Instead of being dependent only on the experience and ability of the system operators, this objective is in general, best achieved if there exists some degree of automation among the reactive control systems. The automatic control of the voltage profile significantly contributes to the enhancement of system security and power quality.

In [4], Fink describes the importance of network voltage control mechanisms in a deregulated system. Unusual patterns of energy interchange may lead some transmission corridors to heavy loading conditions. Coordinated voltage control might play an important role in preventing voltage deterioration or collapse.

Long-term power system voltage instability has been object of concern of various electric utilities around the world. The coordinated utilization of reactive power sources can be an effective way of mitigating this problem.

The results presented in this paper focus on the long-term voltage instability mechanisms, such as, LTC actuation, overexcitation limiters and secondary voltage control. Therefore, only its steady-state gain and limits model the generator voltage primary control. The analysis is performed using the fast simulation tool presented in [5], which is based on the quasi steady-state (QSS) simulator described in [6-7].

The results highlight the enhancement in the system voltage profile at different system scenarios, and the enlargement of the loading margins to prevent voltage instability.

2. Hierarchical Levels

The coordinated voltage control (CVC) is subdivided in three hierarchical levels, namely, Primary Voltage Control (PVC), Secondary Voltage Control (SVC) and Tertiary Voltage Control (TVC), with SVC being an order of magnitude slower than PVC, and TVC being an order of magnitude slower than SVC. Each level plays specific roles, which are described as follows.

<u>PVC Level</u>
The PVC is subdivided into unit control, plant control and LTC actuation.

- Unit Control

This level consists, basically, of the automatic voltage regulator actuation. The regulators try to maintain the machine terminal voltage equal to the reference value provided by the system operators or by the higher level controllers.

- Plant Control

The objective of the plant control, commonly known as Joint Voltage Control (JVC), is to maintain the high-side voltage of the step-up transformer equal to specified values while avoiding reactive power interchange among the plant units.

- LTC actuation

The LTCs are usually used to restore the voltage at the secondary side. They play an important role in the long-term voltage stability phenomena.

<u>SVC Level</u>
The SVC consists of an outer loop that regulates transmission-side voltage at the so-called pilot buses. This is done by adjusting individual generator AVR setpoints, static or synchronous compensators, transformer taps, etc. The pilot bus voltage should consistently represent the voltage in its neighborhood. The SVC actuates in a time scale ranging from 30 to 100 sec. It is considered a regional control.

<u>TVC Level</u>
For optimization, emergency boosting, and coordination of closely-coupled power plants, the transmission-side voltage schedule or setpoint may come from the TVC. The TVC can

assure, in a preventive way, system integrity and security. Usually an Optimal Power Flow program is used for this purpose.

Figure 1 shows the CVC hierarchical control structure for an online implementation.

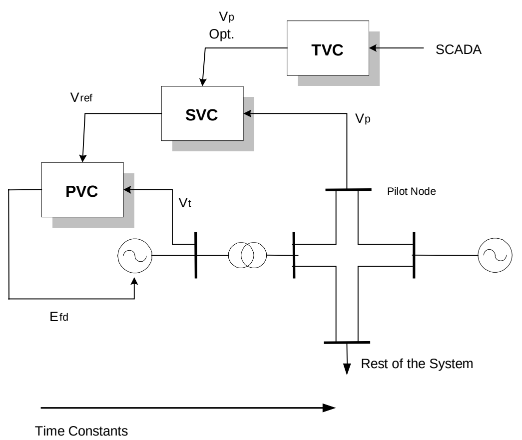

Figure 1 – *CVC Hierarchical Structure*

3. Simulation Tool

The simulation results that will be presented in the next section were obtained from a fast simulation tool, based on the work presented in [6]. The tool has the feature of capturing only mid- and long-term dynamics. The fast dynamics are assumed stable and instantaneous, the final equilibrium point associated with this fast dynamics being represented by a set of algebraic equations.

The basic set of nonlinear equations are given below

$$0 = g(y, x, z_d, z_c)$$
$$\dot{x} = 0 = f(y, x, z_d, z_c)$$
$$z_d(k+1) = h_d(y, x, z_d, z_c(k))$$
$$\dot{z}_c = h_c(y, x, z_d, z_c)$$

where

y represents the algebraic variables (e.g., bus voltages and angles)

x represents the short-term state variables (e.g., machine internal voltages)

z_d represents the long-term discrete state variables (e.g., tap position)

z_c represents the long-term continuous state variables (e.g., AVR's setpoints, which describe the SVC dynamics)

4. Simulation Results

4.1 Characteristics of the Study System

Figure 2 depicts the bulk transfer corridors that lead to the Rio Area, which is a part of the Brazilian Southeastern System. The area has a peak load of approximately 5000 MW in summer time (from January to March). The power flow into the Rio Area comes through four transmission corridors, identified as F1, F2, F3 and F4, in Figure 2. The main sources of reactive support within the Rio Area are 2 x 200 MVAr Synchronous Condensers (SC) at Grajau station, which are jointly generating 290 MVAr at the base case, and the Santa Cruz thermal station. The other reactive sources of interest are located in the transmission system around the Rio Area: Marimbondo, Furnas and L.C.Barreto power stations and Ibiuna SC. The Rio Area equivalent system model used in the simulations consists of 387 ac buses, 678 ac transmission lines and transformers, 30 power plants and 5 SC units.

The Rio Area is subdivided in four subsystems, Furnas (124 buses), Light (127 buses), Cerj (57 buses) and Escelsa (79 buses). The remaining parts of the Brazilian Southeastern System were modeled with static equivalents.

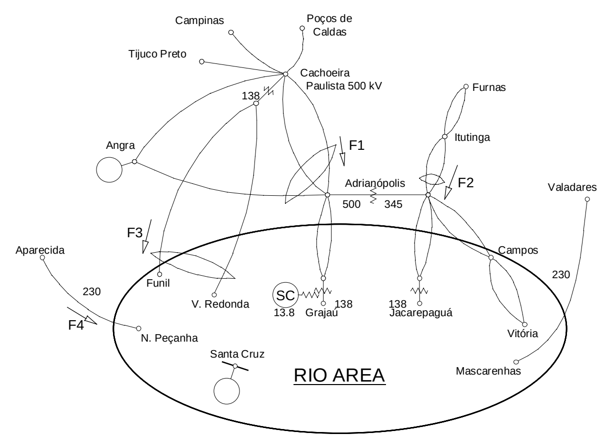

Figure 2 – *Main Transmission Corridors Leading to the Rio Area (Numbers denote voltage level in kV)*

4.2 The SVC Setup

The pilot bus setpoint error is sent to the generator and synchronous condenser units that participate in the SVC. At each unit the error is weighted by the participation factor K_i and integrated. The integrator output signal modulates the AVR setpoint such as to remotely regulate the pilot bus voltage. The presence of the SVC loop requires the step-by-step integration of the corresponding state variables (z_c) in the system model.

Figure 3 shows the inner (PVC) and the outer (SVC) voltage control loops. In the simulations all participating factors were set equal to one and the integrator time constants were set to 100 seconds. The AVR's steady-state gains were set equal to

50 pu/pu, in all generators and SCs. The overexcitation limiters (OEL) were set according to the machine capability.

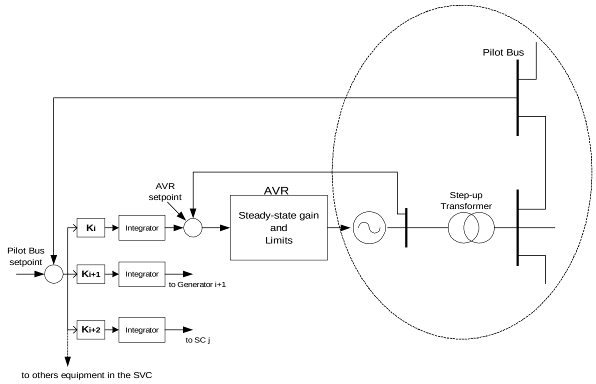

Figure 3 – *SVC Setup*

4.3 Examples

4.3.1 SVC Step Response

In order to assess the SVC closed-loop time response, a step increase of 5% in the reactive load, was applied in the Light Subsystem. The Light Subsystem contains the majority of the loads at the Rio Area. The pilot bus is the Jacarepagua 138 kV Bus depicted in Figure 2. The machines participating in the SVC scheme are Furnas, Marimbondo and Santa Cruz power stations plus Grajau and Ibiuna SCs.

Figure 4 shows the voltage at the pilot bus with and without the SVC scheme, for the step disturbance. It is observed that the closed-loop time response is overdamped with a time constant of about 100 seconds.

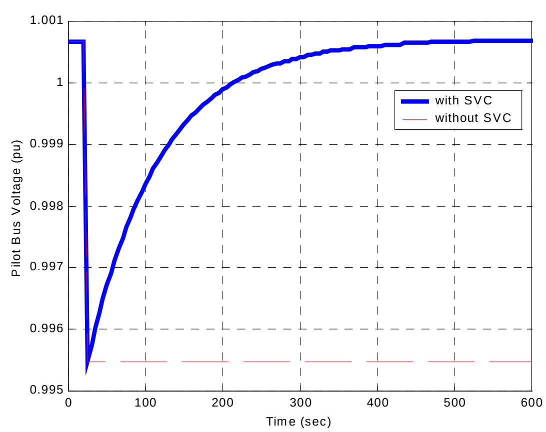

Figure 4 – *Jacarepagua Bus Voltages following a step increase in the Light Subsystem reactive load (with and without SVC).*

4.3.2 Load Variation

Starting from the base case (heavy load condition), a second simulation was performed as follows:

1. From 0 to 300 sec: 5% ramp increase in the active and reactive loads of the Light Subsystem.
2. From 300 to 900 sec: loads remain constant at the final values of Step 1.
3. From 900 to 1200 sec: loads are reduced to the initial values through a ramp.

The trapezoidal-shaped load variation is shown in Figure 5, together with the voltages at the pilot bus (Jacarepagua 138 kV) with and without the SVC scheme. As expected, when no SVC scheme is implemented the system voltages have an upside down trapezoidal shape. Grajau and Ibiuna SC units together with Furnas, Marimbondo and Santa Cruz generating plants participate in the SVC scheme.

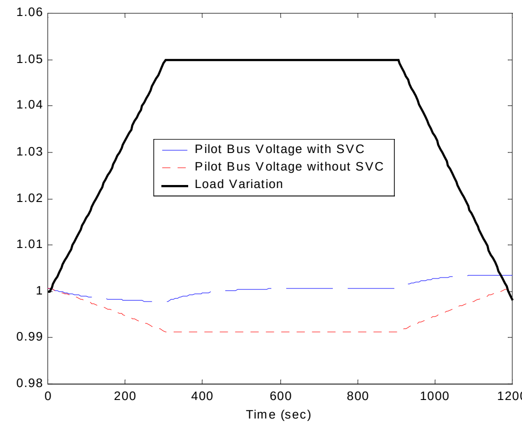

Figure 5 – *Pilot bus voltages with and without SVC and trapezoidal-shaped load variation.*

Figure 6 shows only the voltages at the pilot bus with and without the SVC scheme. The SVC is set to maintain the pilot bus voltage at approximately 1.0 pu. Note that the integral action of the SVC yields a Type 1 system, which produces a constant steady-state error for ramp inputs.

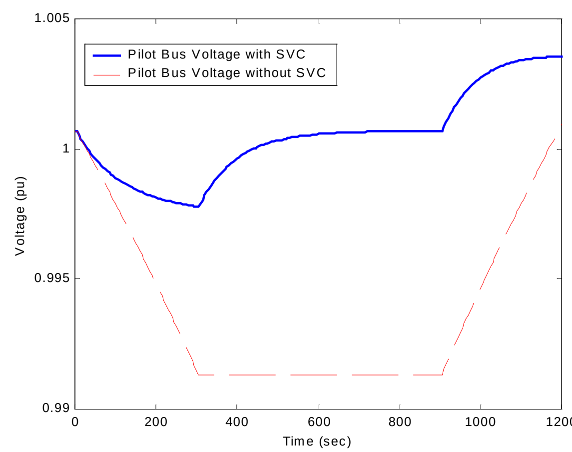

Figure 6 – *Pilot bus voltages with and without SVC following a trapezoidal-shaped load variation.*

Adding a zero-mean gaussian noise with standard deviation of 0.1% to the load variation, the performance of the SVC scheme does not deteriorate, as shown in Figure 7.

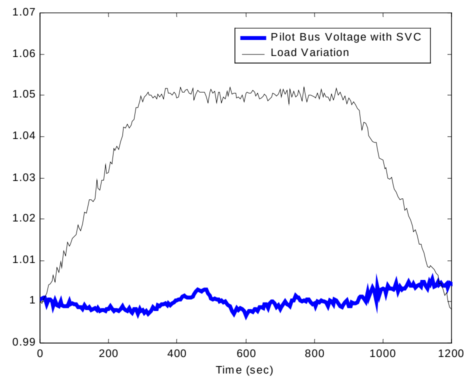

Figure 7 – *Pilot bus voltage with SVC following a trapezoidal-shaped load variation corrupted with gaussian noise.*

The benefits of using the SVC scheme in the Rio Area, were further assessed for a single contingency case and for a case involving gradual and continuous load increase in the Light Subsystem.

4.3.3 Single Contingency Case

The contingency is the outage of the 500kV Angra-Adrianopolis transmission line (TL). The voltage at the pilot bus is 1.0 pu before the contingency and 0.958 after the contingency. The control objective is to maintain the voltage at the pilot bus at 0.98 pu, for this contingency.

Three SVC schemes, with different number of voltage control equipment regulating the pilot bus voltage, i.e., participating in the SVC, are analyzed.

- Case 1 – only the Jacarepagua LTC;
- Case 2 – Jacarepagua LTC and Grajau SC;
- Case 3 – Jacarepagua LTC, Grajau SC and Santa Cruz thermal units.

Figure 8 shows the voltage at the pilot bus in all three cases. The curves show that the control objective was only achieved in Case 3 (dotted line). In Cases 1 and 2 (solid and dashed lines, respectively) there are steady-state errors, owing to the LTC reaching its maximum tap limit in the former case and to the Grajau SC reaching its overexcitation limit in the latter case.

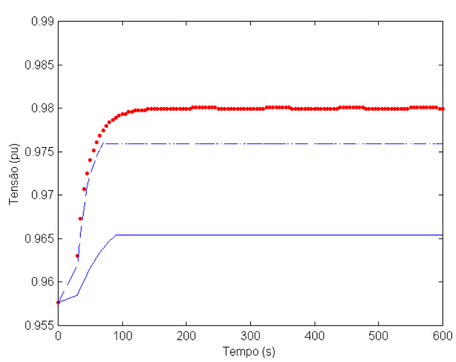

Figure 8 – *Pilot Bus Voltage. Solid – Case 1; Dashed – Case 2; Dotted – Case 3*

Figure 9 shows the Grajau terminal voltage in all three cases. It is worth noting that the voltage is practically the same in Cases 2 and 3, even though the voltage at the pilot bus is quite different (see Figure 8). This difference is due to the role played by the Santa Cruz thermal generator, which also regulates the pilot bus in Case 3. Note that the Grajau SC voltage remains almost constant in Case 1, since it does not participate in the SVC.

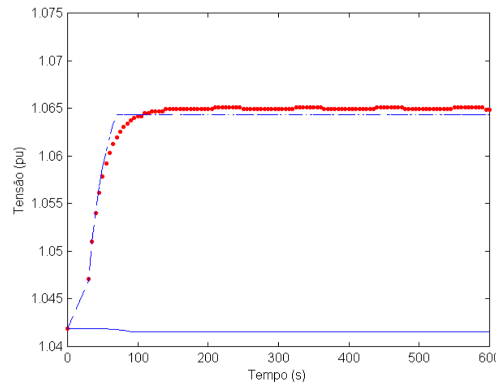

Figure 9 – *Terminal Voltage of Grajau SC. Solid – Case 1; Dashed – Case 2; Dotted – Case 3*

Figure 10 shows the Grajau SC field current for the three cases. In Case 1, one can note the interactions between the Jacarepagua LTC and the primary voltage control of the Grajau SC. In Case 2 Grajau OEL is reached at 80 seconds of simulation. The Grajau OEL is not reached in Case 3, due to the participation of the Santa Cruz thermal generators in the SVC.

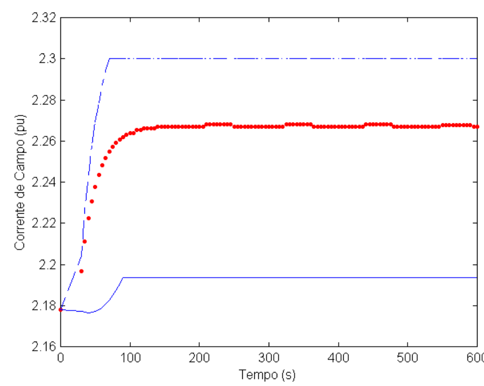

Figure 10 – *Field Current of Grajau SC. Solid – Case 1; Dashed – Case 2; Dotted – Case 3*

4.3.4 Loading the Light Subsystem

This simulation had the objective of showing not only the benefits on the overall system voltage profile, but also the gains in loading margin, when using a SVC scheme in the Rio Area.

A load ramp was applied to the Light Subsystem (30% constant-power-factor load increase in 1000 seconds). The loads at the remaining subsystems were held constant. Only Cases 1 and 3, described in Section 4.3.3, were analyzed. The objective of the SVC was to regulate the pilot bus voltage at 1.0 pu

Figure 11 compares the pilot bus voltage for the two cases. Voltage instability is seen to occur shortly before 800 seconds of simulation. In Case 1 (solid line), the voltage deteriorates as the system is loaded. On the other hand, in Case 3 (dotted line), the voltage at the pilot bus is held constant as long as the reserve of reactive power generation exists. One can note that when the last resource of reactive power hits its limit, a sharp decrease in the voltage at the pilot bus is observed.

The utilization of a SVC scheme did not increase the maximum loadability of the system for these two cases, as both voltage curves collapse at the same time instant.

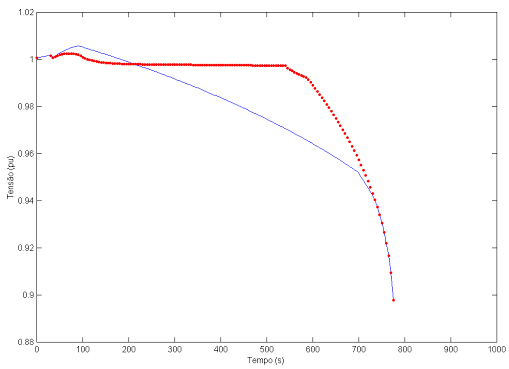

Figure 11 – *Pilot Bus Voltage. Solid – Case 1; Dotted – Case 3*

Figure 12 shows the voltage profiles for all 387 buses of the system.

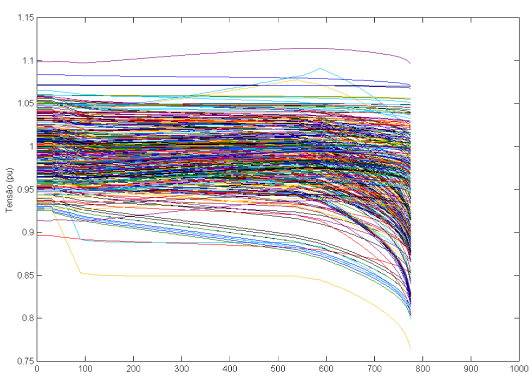

Figure 12 – *Overall System Voltage Profile*

To investigate the ability of a SVC scheme to increase the maximum loadability of the Light Subsystem, Case 4 was setup as follows:

- Case 4 – The same equipment considered in Case 3, plus Furnas and Marimbondo power plants and Ibiuna SC.

These three additional reactive sources included in the SVC scheme are a bit distant from the Light Subsystem.

Figure 13 shows the pilot bus voltage for the simulations of Case 1 (solid line) and Case 4 (dotted line). It is clearly noted the increase in the maximum loadability limit with the SVC scheme adopted in Case 4.

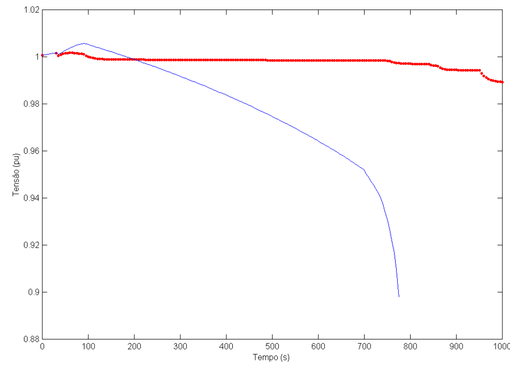

Figure 13 – *Pilot Bus Voltage. Solid – Case 1; Dotted – Case 4*

In order to show the voltage instability occurring also in Case 4, we stressed the Light Subsystem to a 40% constant-power-factor load increase. Figure 14 shows the pilot bus voltage for this higher loading condition.

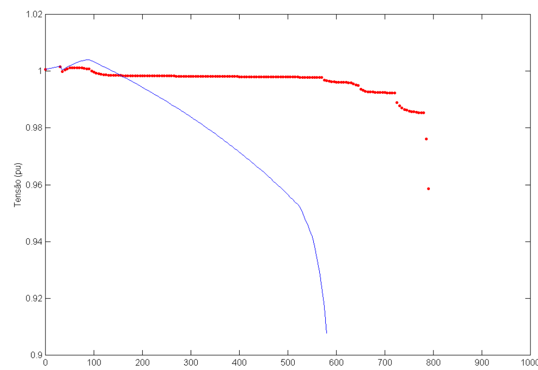

Figure 14 – *Pilot Bus Voltage. Solid – Case 1; Dotted – Case 4*

4.3.5. Influence of Pilot Bus Selection in the Control Performance

A key factor in coordinated voltage control, the selection of pilot buses, can substantially modify the overall performance of the control scheme. To illustrate this point, we setup new cases of load ramping in the Light Subsystem.

The voltage profile at a critical system bus (Jacarepagua) was monitored for a loading increase of 20% in the Light Subsystem considering different SVC strategies. Constant power factor loads were increased linearly with time. The additional power needed was supplied by specified system generators according to their steady-state speed droop.

Figure 15 shows the voltage at Jacarepagua 138kV for the three cases described as follows:

- Case 5 – Pilot bus is Jacarepagua 138kV. The voltage at pilot bus is regulated at 1.0 pu. Three generating plants and two SC participate in the SVC.

- Case 6 – Pilot bus is Cachoeira Paulista 500kV. The voltage at pilot bus is regulated at 1.06 pu. The same generating plants and SC considered in Case 5, participate in the SVC.
- Case 7 – No SVC implemented.

In Case 5 the pilot bus is within the Rio Area, at the 138 kV network and closer to the major loads, whereas in Case 6 the pilot bus is at a major EHV transmission network that feeds the Rio Area.

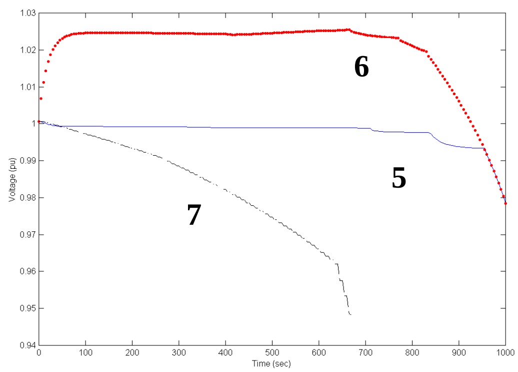

Figure 15 – *Jacarepagua Bus Voltage. Solid – Case 5; Dotted – Case 6; Dashed – Case 7*

It can be noted that in Cases 5 and 6, the Rio Area can be further loaded before a voltage collapse situation takes place. The load margin limit was virtually the same irrespective to the location of the pilot bus.

Despite having the same voltage stability margin, Case 6 has advantages (not shown here) over Case 5, since the voltage control at a critical point of the 500 kV transmission corridor (Cachoeira Paulista) gives better overall performance to the system along the whole daily and seasonal load curve.

6. Conclusions

The preliminary results involving the use of a SVC scheme in the Rio Area showed the benefits gained regarding voltage profile and security.

The results also showed the importance of properly selecting the pilot bus and the reactive power sources participating in the SVC scheme. Preliminary results for the Rio Area indicate that regulation at higher voltage levels leads to a better overall control performance.

The simulations showed the benefits of including some remote reactive sources in the SVC scheme to control the voltage profile and increase the loading margin of the Rio Area.

Acknowledgments

Professors G. N. Taranto and D. M. Falcão thank CEPEL for partly sponsoring this project.

References

[1] J. P. Paul, J. Y. Léost, J. M. Tesseron, "Survey of the Secondary Voltage Control in France: Present Realization and Investigations", *IEEE Transactions on Power Systems*, Vol. 2, No. 2, pp. 505-511, May 1987.

[2] S. Corsi, P. Marannino, N. Losignore, G. Moreschini, G. Piccini, "Coordination between the Reactive Power Scheduling Function and the Hierarchical Voltage Control of the EHV ENEL System," *IEEE Transactions on Power Systems*, Vol. 10, No. 2, pp. 686-694, May 1995.

[3] H. Vu, P. Pruvot, C. Launnay, Y. Harmand, "An Improved Voltage Control on Large-Scale Power System," *IEEE Transactions on Power Systems*, Vol. 11, No. 3, pp. 1295-1303, August 1996.

[4] L. H. Fink, P. J. M. Van Son, "On System Control Within a Restructured Industry," *IEEE Transactions on Power Systems*, Vol. 13, No. 2, pp. 611-616, May 1998.

[5] W. J. Causarano, D. M. Falcão, G. N. Taranto, "A Fast Domain Simulation Method for Voltage Stability Assessment," *Proceedings of the VI SEPOPE*, Salvador, BA, May 1998.

[6] T. Van Cutsem, "An Approach to Corrective Control of Voltage Instability Using Simulation and Sensitivity," *IEEE Transactions on Power Systems*, Vol. 10, No. 2, pp. 616-622, May 1995.

[7] T. Van Cutsem, C. D. Vournas, "Voltage Stability Analysis in Transient and Mid-term Time Scales," *IEEE Transactions on Power Systems*, Vol. 11, No. 1, pp. 146-154, February 1996.